

SOLAR COSMIC RAY EFFECTS IN THE LOWER IONOSPHERE

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INTRODUCTION

The polar cap absorption (PCA) events are the most remarkable geophysical phenomena in the high-latitude ionosphere. Their effects are extended on the whole polar region in the both hemispheres. The PCA events are caused by the intense fluxes of the solar cosmic rays (SCR) which are generated by the solar proton flares. Entering into the Earth's magnetosphere and ionosphere the SCR fluxes create excessive anomalous ionization at the ionospheric heights of 50-100 km which exceeds usual undisturbed level of ionization in several orders of magnitude. The PCA events can be considered as catastrophe in relation to the polar ionosphere because all radiosystems using ionospheric radiochannel ceased to operate during these events. On the other hand the abnormally high level of ionization in the ionospheric D-region during the PCA events create excellent opportunities to conduct fruitful aeronomical research for the lower ionosphere. Obvious scientific and practical importance of the PCA events leads to publishing of special PCA catalogues. The Soviet scientists have prepared several of such catalogues (LOGACHEV et al., 1983). The ionospheric effects caused by the SCR fluxes were profoundly described in the classical paper (BAILEY, 1964). Nevertheless several aspects of this problem are not studied properly. This paper is an attempt to clarify these questions.

ELECTRON DENSITY PROFILE VARIATIONS DURING THE PCA EVENTS

The D-region ionization level during the PCA events is due to two main factors: SCR flux intensity and Solar luminosity level. Excellent example of this situation is the PCA event of April, 1969, which is shown at Figure 1. Curves 1 and 2 indicate the variations of 30 MHz riometer absorption correspondently at Vostok Station (Antarctica, invariant latitude $\Phi' = 83.3^\circ\text{S}$) and at the ice drifting station North-Pole-16 ($\Phi' = 81^\circ\text{N}$); curve 3 - the solar protons with $E \geq 10$ MeV intensity variation recorded at the "Explorer-10" satellite. The small vertical arrows at the time axis indicate the local noon at Vostok Station. The "North Pole-16" Station was fully illuminated by the Sun during the whole event. One can see day-to-night absorption variations at Vostok Station while the absorption variation at "North Pole-16" Station even in small details repeat the SCR flux variations.

It is interesting to summarize reliable data on the electron density profiles during the PCA events for daytime and nighttime conditions separately. Such data for the daytime PCA events are shown on Figure 2. The rocket measurements data are shown by the solid curves and the ground-based measurements data - by the dotted lines. The numbers on the curves indicate correspondent absorption values. The curves for great values of absorption correspond to greater values of electron density and are located at comparatively low heights (sometimes as low as 43 km). Identical

situation is observed during the nighttime PCA events (see Figure 3). Naturally, the value of absorption (and correspondent N values) during nighttime is lower in comparison with the same daytime values. The maximum of electron density is located at 80-85 km. The data of Figures 2 and 3 give additional evidence of average solar proton energy which caused the PCA events. For the daytime events such energy is $E_0 \geq 10$ MeV, while for the nighttime events it is $E_0 \approx 5$ MeV.

There is no detailed study of the F-region electron density behaviour during the PCA events. General opinion is that F-region of ionosphere does not change under influence of SCR fluxes. There are experimental evidence of it (HANSUCKER, 1973). The numerical model calculations of the ionization rate during the PCA events confirm such conclusion (BAILEY, 1964). Strictly speaking, there is possibility to have considerable value of ionization rate from SCR with $E_0 \approx 800$ MeV at the heights of 200 km. In this case one must take into account various processes of nuclear interactions of solar protons with atmosphere (such as evaporation, cascade chains etc.). On the other hand, solar protons of such energies do not create any ionization in the D-region.

EFFECT OF MIDDAY RECOVERY OF ABSORPTION

The riometer data from auroral station reveal the effect of a notable decrease of absorption during some PCA events in hours around geomagnetic noon. This phenomenon was called midday absorption recovery effect. Remarkable peculiarity of this effect is that none of existing aeronomical models of PCA-disturbed D-region could reproduce it. Therefore there are strong reasons to believe that this effect is due to the magnetospheric processes. One of it could be anisotropic pitch-angle distribution fo SCR during the solar protons movement toward dayside in the quasi-trapped region. Numerous satellite measurements show that in these situations the solar proton trajectories are located deeply inside in the closed field lines region and a boundary of the SCR penetration moves toward the high-latitude at prenoon MLT hours (BURROWS, 1972). This effects is due to different degree of the ring current asymmetry during the PCA events (WILLIAMS and HEURING, 1973). A natural explanation of the effect could be phenomenon of magnetosphere asymmetry and caused by it diurnal variation of the geomagnetic cut-off threshold with its increasing at daytime. This explanation contradicts with obvious fact that the midday recovery effect is observed not in every PCA event at auroral latitudes. It was found that this effect preferably occurs during PCA events produced by solar flares on the eastern Sun hemisphere (ULYEV, 1988). Besides that, the periods of the midday recovery appearance the satellite data demonstrate notable softening of the SCR energetic spectra. Occurrence of this effect diminishes sharply at invariant latitudes greater than 70° as well as at latitudes less than 62° . The same thing is evident with increasing geomagnetic activity level. This situation is shown on Figure 4, taken from (ULYEV, 1988). So presence/absence of the midday recovery effect gives information about heliolongitude of a flare which produced PCA event as well as about type of the SCR energetic spectra.

CONJUGACY EFFECTS

The early conjugate observations (SAUER, 1968) during PCA events revealed quite different response of the polar ionosphere in opposite hemispheres to the solar protons fluxes. A number of factors can be responsible for such situation. Amongst them are: different solar illumination regime at the observation points; a different heliolongitude of a solar flare which caused PCA event (HAURWITZ et al., 1965); character of the interplanetary magnetic field (IMF) orientation during the PCA events (REID and SAUER, 1967). Up to now there is no full understanding of a role of each of these factors in the lower polar ionosphere behaviour during the PCA events. Recently one more pair of the high-latitude conjugate stations began to operate: Mirny (Antarctica) and Spitzbergen (Arctica). Their invariant latitude is 75° .

Figure 5 shows riometer absorption variations at Mirny (dotted line) and Spitzbergen (solid line) during the June 6-9, 1979 PCA event together with the concurrent IMF parameters. The North Hemisphere lower ionosphere was fully sunlit at this time while it was in complete darkness in the South. One could expect that under the same solar proton fluxes illumination riometer absorption at Spitzbergen would significantly exceed absorption at Mirny. In fact, absorption magnitude at Mirny was even greater sometimes than at Spitzbergen. The solar flare which caused this PCA event occurred on 5 June 1979 on the eastern solar hemisphere (LOGACHEV et al., 1983), i.e. long before the PCA event started to be developed. Therefore, one could not expect any kind of the SCR fluxes anisotropy at this time. We think that the observed North-South asymmetry in the SCR intensity during the 6-9 June 1979 PCA event can be successfully explained in the framework of the magnetotail model proposed by SIBECK et al. (1985). One can see almost exact coincidence of the absorption increase at Spitzbergen with a sharp $+B_y$ rise. This absorption increase took place at the morning hours (in MLT) what is in a good agreement with the GOSLING et al. (1985) model of a plasma distribution in a distant tail. Low-energy solar protons with Larmor radius equal to $1.5 - 2 R_E$ responsible for riometer absorption can penetrate into the tail lobes through described by SIBECK et al. (1985) "windows" without any trouble.

Concurrently with a $+B_y$ increase a similar rise of the $-B_z$ IMF component took place (see Figure 5). This situation is favourable for a plasma penetration to the South Hemisphere from the interplanetary space. Perhaps, a combination of these factors provided conditions for a such unusual North-South absorption distribution which is shown on Figure 5. A conclusion can be made that the results of riometer observations at conjugate points during 6-9 June 1979 PCA event give a strong confirmation of a distant magnetotail model proposed by SIBECK et al. (1985). These riometer observations also support idea of a strong IMF control of a distant magnetotail structure. The solar protons whose Larmor radius is more than $5 R_E$ ($E \geq 30$ MeV) perhaps are not influenced by the IMF orientation during their entering into magnetosphere. Actually these protons give a small contribution to riometer absorption.

RADIOCOMMUNICATION EFFECTS

It is well known that the PCA absorption magnitude strongly depends on frequency. This dependence can be described by equation:

$$A_1/A_2 = (f_2/f_1)^n$$

where A_1 - absorption values at frequency f_1 ; A_2 - absorption values at frequency f_2 ; $n = 1.5-2$. Usually riometers operate at frequency 30 MHz. So, if we have absorption at 30 MHz equal to, say, 10 dB, a correspondent absorption at $f = 1$ MHz will be ≈ 60 dB; at $f = 100$ MHz - 1 dB, at $f = 150$ MHz - 0.4 dB. These evaluations are given for the case of vertical incidence of radiowave on the ionosphere. In the case of oblique incidence absorption value would be increased in accordance with the secant law, i.e. it would be greater in 5-7 times for oblique radiopath of 2000 km length. The experimental data show that the greatest influence of the PCA events one can expect at the radiopaths located entirely in the polar latitudes. In this case the lowest usable frequencies (LUF) considerably increase with concurrent diminishing of the maximal usable frequencies (MUF). The final result is a significant decrease of operating frequency range including the cases of complete disappearance of communication. It is clear that the PCA events influence would be greater at the radiopaths operating at LF and VLF radiowaves. Such navigation systems like Loran-C could not operate properly under PCA conditions. Crude estimations show that the PCA event with maximum absorption equal to 20 dB at 30 MHz could significantly diminish efficiency of all radiosystems operating at frequencies up to 120 MHz. Recent series of the PCA events in March 1989 of very long duration demonstrate a strong necessity to develop a reliable model for prediction of the PCA events appearance. Preliminary data on the March, 1989 PCA events intensity are given below (Soviet riometers in Arctica and Antarctica data):

PCA event 1. Start 08.03 at 07-30 UT; Finish 14.03 at 21-00 UT;

$A_{\max} = 10.5$ dB at 08-00 UT 13.03.89.

PCA event 2. Start 17.03 at 21-30 UT; Finish 20.03 at 15-00 UT;

$A_{\max} = 6.65$ dB at 08-05 UT 18.03.89.

PCA event 3. Start 23.03 at 20-00 UT; Finish 25.03 at 01-00 UT;

$A_{\max} = 2.4$ dB.

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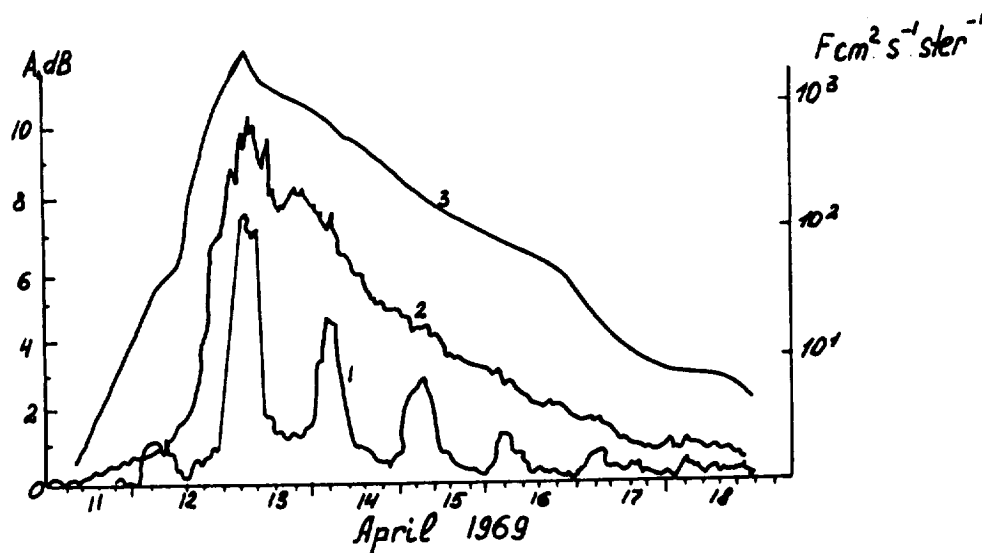


Figure 1. The April 1969 PCA event:

- 1 - riometer absorption at Vostok Station
- 2 - riometer absorption at North-Pole-16 Station
- 3 - Solar proton with $E_0 \geq 10$ MeV flux

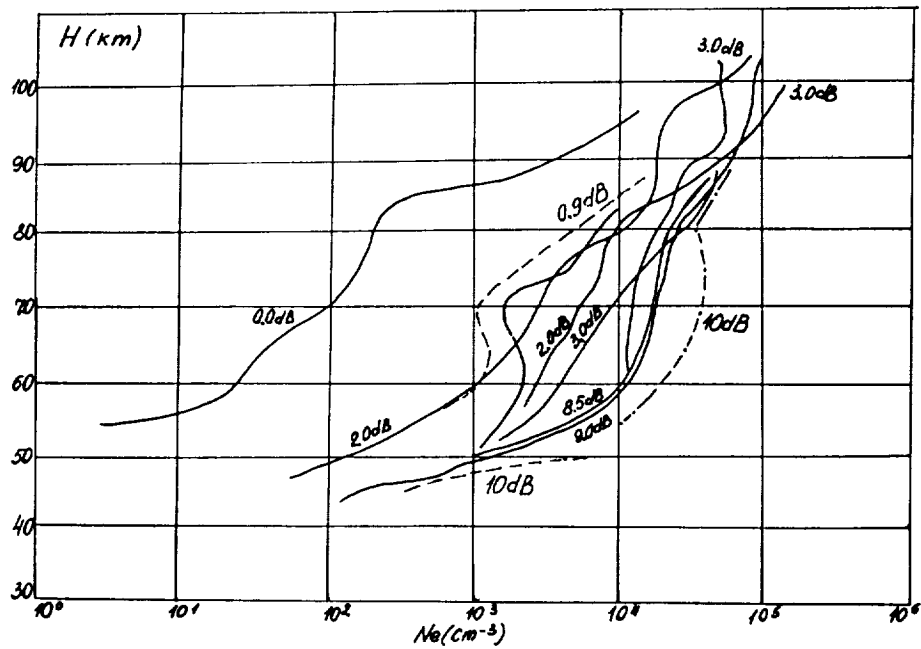


Figure 2. Electron density profiles for daytime PCA events.

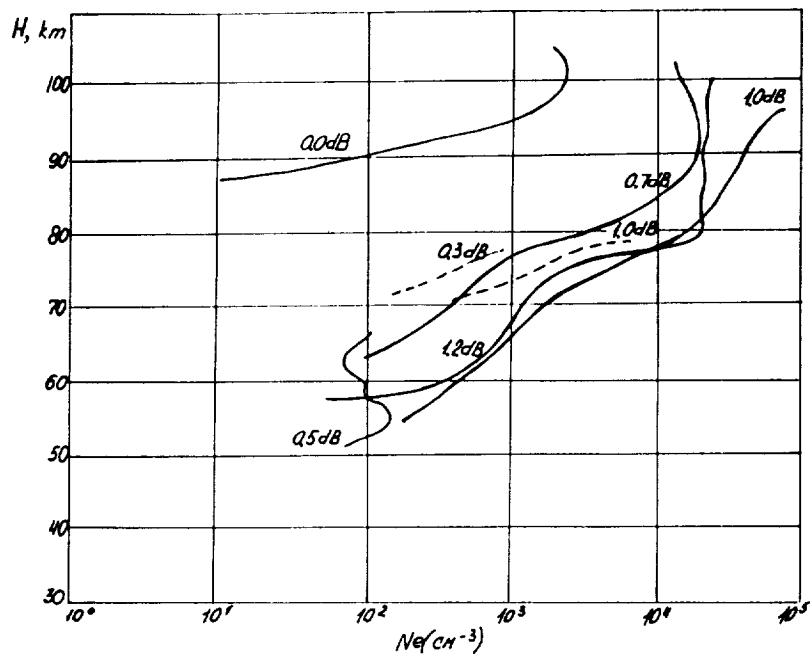


Figure 3. Electron density profiles for nighttime PCA events.

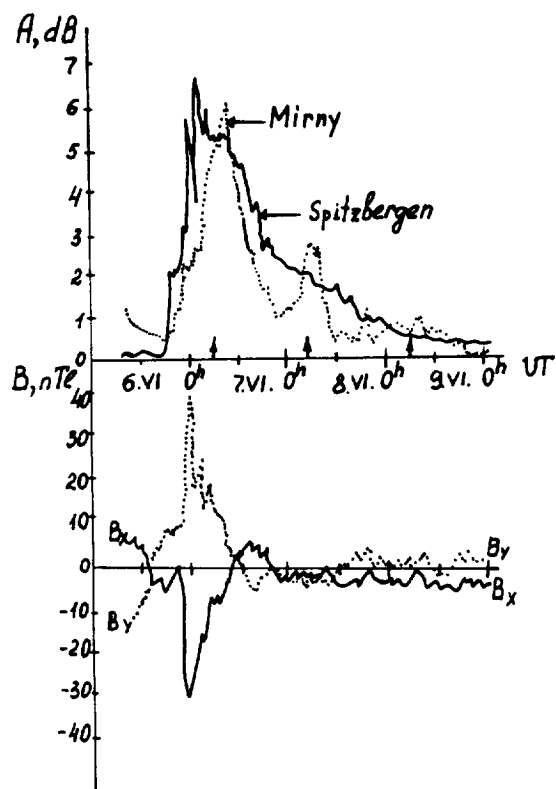


Figure 4. Riometer absorption variations at Mirny and at Spitzbergen during the 6-9 June 1987 PCA event (upper panel) together with corresponding variations of the IMF components (lower panel).

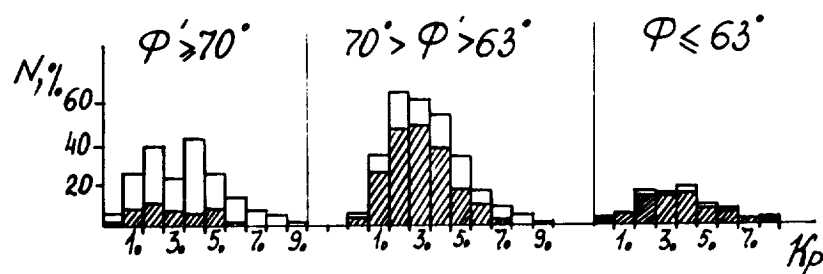


Figure 5. The PCA events occurrence in 1970-79 in various latitudinal belts: hatched parts: events with midday recovery effect.